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ORIGINAL PAPER

Investigations of mechanisms of laser radiation absorption at PALS

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Abstract. Absorption mechanisms of laser radiation have been studied in the experiments at Prague Asterix Laser System (PALS – Prague, the Czech Republic) with normal incidence of iodine laser beams on plane massive targets made of Al and Cu. The investigations were performed for the first and the third harmonics of iodine laser radiation, four focal spot radii (40–160 μm) and laser pulse duration of 250 ps full width at half maximum (FWHM) at energy of 290 J. For the given target irradiation conditions, the laser intensity was varied in a range of 2.6×10^{15}–4.1×10^{16} W·cm^{-2}. Measurement of crater parameters by a cellulose acetate – replica technique and a three-frame interferometry were used as diagnostic tools. The experimental results allowed us to distinguish two areas of target irradiation parameters corresponding to resonance and inverse bremsstrahlung absorptions, respectively.

Key words: collisional absorption • crater volume • electron density distribution • interferometry • iodine laser • resonance absorption

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Introduction

Studing the ablation action on a solid target of the laser beam in a wide range of radiation intensity is at the forefront in the fields of physics related to inertial confinement fusion, astrophysics, studies of the properties of various materials, their equation of state and methods of technological processing [1–4, 12]. This work relates to the first area and is devoted to research of the mechanism of ablation pressure producing in the specific conditions of irradiation of the inertial fusion target, where the absorption of laser radiation is due to the resonance mechanism and the most part of the absorbed laser energy converses into fast electrons energy [5–8].

In the processes of laser-solid target interaction two stages are taken into consideration: (i) absorption of laser energy and (ii) crater creation in the target [6]. The laser energy transfer into the target terminates with the laser pulse end. Then, the laser beam action involves subsequent processes into an irradiated target, such as shock wave generation and crater creation. The shock wave propagating in the target causes melting and evaporation of the target materials. When the shock wave energy becomes lower than the energy necessary for the target material evaporation, the process of the crater creation is stopped. In spite of that, crater parameters like shape, sizes and volume deliver some information about the efficiency and mechanism of the laser radiation absorption.

In the paper we present the results for large laser intensities (2.6×10^{15}–4.1×10^{16} W·cm^{-2}) and two dif-

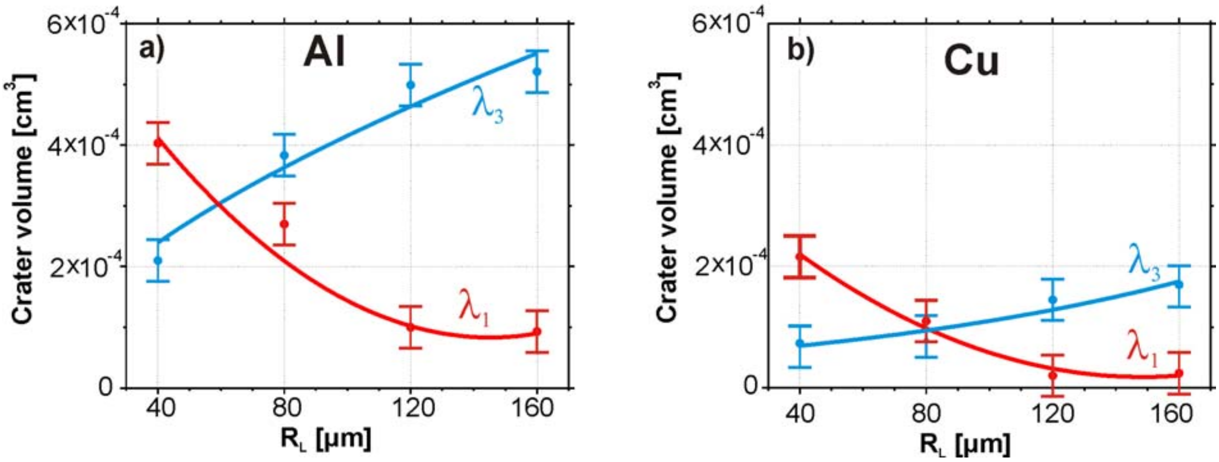

Fig. 1. Volumes of craters produced in Al (a) and Cu (b) targets at laser energy 290 J for both harmonics used and different focal spot radii.

ferent target materials: aluminum and copper. Experiments were carried out with the use of the PALS [9].

Experimental set-up, conditions and results

The laser provided a 250 ps (FWHM) pulse with an energy of 290 J. The plasmas were generated with normal incidence of an iodine laser beam on the surface of planar solid targets made of Al or Cu. Two harmonics of laser radiation, the first one with a wavelength of $\lambda_1 = 1.315$ μm and the third one with $\lambda_3 = 0.438$ μm, were used. The investigations were performed for four focal spot radii (R_L) at the target surface: 40, 80, 120, and 160 μm.

In order to obtain information about crater characteristics, the crater replicas were made of cellulose acetate. To reconstruct qualitatively the crater shape, profiles of the crater replica in the chosen cross-section were digitized and the data used for calculations. For studying plasma electron densities a 3-frame interferometric system [10] with automatic image processing was used.

The crater volumes for both the crater materials and two harmonic as a function of the focal spot radius are plotted (Fig. 1). In the case of the first harmonic the crater volume has a maximum value at the minimum R_L. Next, the crater volume decreases with growing R_L up to $R_L = 120$ μm. In the R_L range of 120–160 μm the crater volume changes marginally. Quite the contrary, the crater volume produced by the third harmonic of laser radiation is a growing function of R_L. For small values of R_L, the crater volume corresponding to the first harmonic is greater than that produced by the third harmonic.

It should be pointed out that in our interferometric investigations the main attention was paid to the plasma parameters just after the laser pulse end, i.e. when the laser radiation absorption is already completely terminated. The plasma produced directly by the laser action on the target "remembers" a history of its origin. Taking into account that the laser pulse duration at the base is greater than 1 ns, therefore interferograms recorded in an instant of 2 ns were used in our further analysis. At post-pulse times the plasma emission is induced by secondary processes like shock wave generation in the target and crater creation and such plasma does not deliver information about the earlier processes. In Fig. 2, the electron density distributions in the Al (2a) and Cu (2c) plasmas in 2 ns for all the focal spot radii in the form of equidensitograms are presented. The most interesting plasma parameter appeared to be the total electron number (N_e) in the plasma plume, computed on the basis of the above diagrams. The total electron number in combination with the crater volume could provide essential information about mechanisms of the laser radiation absorption. Therefore, for the cases under investigation the ratios of total electron number to crater volume were calculated. The ratio values allow to draw the diagrams, which are presented in Figs. 2b and 2d. These diagrams say how many electrons participate in creation of the crater volume unit (1 cm^3). One can see that there are great differences between the curves for λ_1 and λ_3, whereas forms of these curves for the same wavelength are qualitatively similar for both the target materials. The point of intersection of λ_1 and λ_3 graphs for Al and Cu corresponds approximately to the same value of R_L equal to 90 μm. Distinctions have quantitative character, namely creation of the same crater volume requires in the case of Cu target the electron amount greater about twice than that necessary in the case of Al, independently of the wavelength of laser radiation.

Discussion of the experimental results and conclusions

The diagrams in Figs. 2b and 2d show that in the case of the third harmonic the number of electrons produced during the laser beam action per crater volume is practically constant for the Al and Cu targets. It means that the mechanism of laser energy transfer into the target via plasma should be the same in the whole range of R_L. It is well known that the kind of laser radiation absorption is determined by the parameter $I\lambda^2$. Lower values of this parameter prefer the inverse bremsstrahlung absorption, whereas the higher ones – the resonance absorption. The resonance absorption, which is accompanied by the generation of fast electrons, should

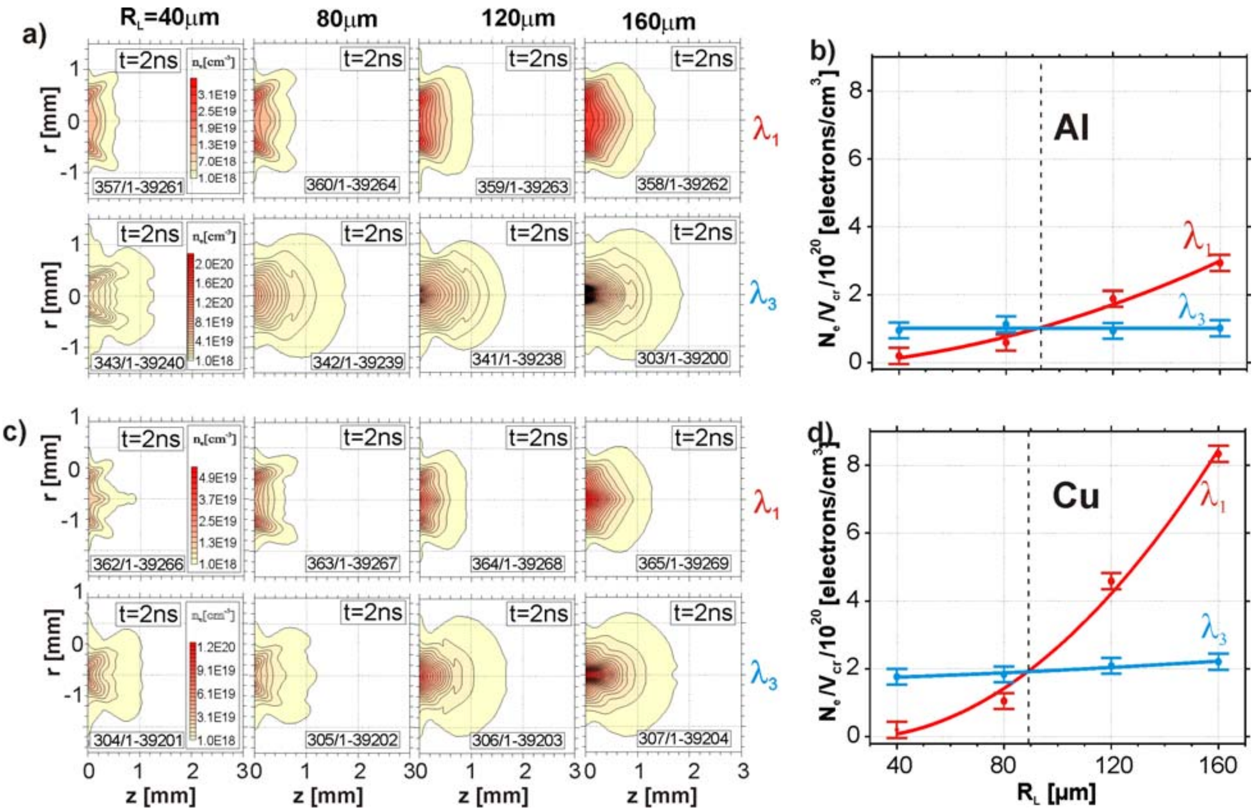

Fig. 2. Electron density distributions and N_e/V_{cr} ratio of Al (a, b) and Cu (c, d) plasmas in 2 ns for different focal spot radii and both wavelengths.

however change the linear form of diagrams, particularly, in the part corresponding to the smallest R_L. So, the experimental values of the parameter $I\lambda^2$ for the third harmonic, varying between 4.9×10^{14} and 7.8×10^{15} W·μm²·cm⁻², are appropriate for laser radiation absorption primarily by inverse bremsstrahlung.

In the case of the first harmonic the parameter $I\lambda^2$ is varied in the range of 4.5×10^{15}–7.1×10^{16} W·μm²·cm⁻², so the range of this parameter is one order of magnitude greater than that in the case of the third harmonic. For $R_L < 90$ μm the first harmonic curves for both the targets lie below the graphs for the third harmonic. It means that smaller numbers of electrons are needed for the production of the same crater volume. In such a case this smaller number of electrons must be compensated by greater energy of electrons. Hence, one can conclude that the greater energy of electrons is induced by other mechanism of laser energy absorption than that in the case of the third harmonic, i.e. by resonance absorption. At $R_L = 40$ μm the ratio of total electron number to crater volume for the first harmonic constitutes only 20 or 10% of this value for the third one related to Al and Cu, respectively. It means that a substantial part of the laser energy is deposited in the form a very non-Maxwellian high-temperature tail on the electron velocity distribution. However, the distance between the graphs for λ_1 and λ_3 decreases very fast with growing R_L, so as to cross each other at $R_L \approx 90$ μm for both the target materials. For $R_L > 90$ μm the increase of the ratio of electron number to crater volume with growing R_L is continued. So, to produce the same crater volume a greater total electron number is necessary than that in the case of the third harmonic. It proves that the resonance absorption efficiency, having its maximum at $R_L = 40$ μm, drops drastically with growing R_L. The dominant role of the resonance absorption is gradually lost, being shifted to the inverse bremsstrahlung absorption. However, the efficiency of the latter for λ_1 is considerably lower than that for λ_3 due to higher temperature of plasma produced by the first harmonic. Assuming that for $R_L = 160$ μm the pure inverse bremsstrahlung absorption occurs in the case of both the harmonics, the ratios of crater volumes for λ_3 and λ_1 taken from the experimental data as well as taking into account that the crater volume is proportional to $K_{ab}\sigma E_L$(where: $\sigma = E_{sw}/E_{ab}$ – ablation loading efficiency; E_{sw} – the shock wave energy and E_{ab} – the laser radiation absorption, [6]) and $\sigma_3/\sigma_1 = 5$ (determined on the basis of the theoretical calculation) the difference in the plasma temperature for λ_3 and λ_1 can be estimated. As a result, we obtain that $T_1 \approx 3T_3$. Since the inverse bremsstrahlung absorption is an ordinary absorption by Coulomb collisions, so the efficiency of laser radiation absorption in this case depends on the rate of electron-ion collisions, which is lower for higher plasma temperature. In consequence, the laser radiation absorption by the inverse bremsstrahlung mechanism is much less effective in the case of the first harmonic under the same target irradiation conditions.

Finally, we would like to point out that for the laser energy of 290 J two different mechanisms of laser radiation absorption were identified, i.e. resonance absorption, appropriate for higher intensity of laser radiation and longer wavelength, and inverse bremsstrahlung absorption. The former is, in fact, mainly observed for the first harmonic of laser radiation at the minimum focal spot radius. The latter is dominant in the case of the third harmonic in the whole range of the focal spot radius used. It appears that the value of $I\lambda^2$, equal to about 10^{15} W·μm^2·cm^{-2}, lies on the border of two areas corresponding to dominance of two different mechanisms of the laser radiation absorption.

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